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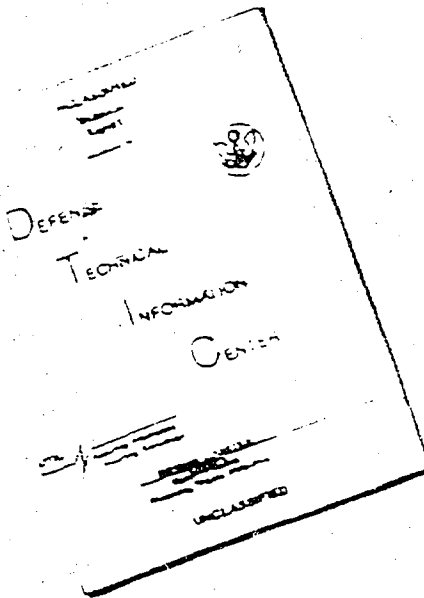
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R.A.R.D.E. REPORT 1/65

A telemetry system for the measurement of the yaw of a
projectile throughout the major part of its trajectory

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A telemetry system for the measurement of the yaw of a projectile throughout the major part of its trajectory

I.O.F. Amery (B2)

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Summary

A telemetry system is described which allows measurement of the yaw of spinning projectiles at all angles of fire over long trajectory distances by continually sensing the attitude of the projectile with respect to the sun and transmitting this information back to the ground in the form of a pulse position modulated signal. The system has been successfully tested in extensive firing trials.

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Approved for issue:

F.J. Ash, Principal Superintendent, 'B' Division

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INTRODUCTION

1. The measurement of the yawing motion of a projectile in flight has for a long time been the subject of considerable interest. Yaw measurement is not only important as an immediate practical aid to the designer but also as a basis for fundamental research on the stability of a spinning shell. For the classical investigations of Fowler, Gallop, Lock and Richmond (1) which were restricted to flat trajectories and small angles of yaw, the experimental data obtained from yaw cards were sufficient, but the treatment of high angle fire with the possibility of large yaw near the vertex, requires measurement of yaw and spin to extend over as much of the trajectory as possible.
2. The object of this paper is to describe a method first proposed by D.Cooke in 1962 (2), of measuring a component of yaw and the spin rate of a spin-stabilised projectile over the whole of its trajectory. The frequency with which measurements are made is the same as the spin rate of the projectile. The method can be used at all angles of fire.
3. The basis of the method is that a transducer and a radio transmitter in the projectile produce and send to the ground information from which the angle between the projectile axis and the direction of the sun's rays can be deduced together with the spin rate. Neither radio telemetry nor the use of the sun's rays as a reference is new in the field of yaw measurements. The novelty of the method to be described is that the two techniques are combined in such a fashion as to eliminate most of the disadvantages of each when used separately.
4. In the following a brief survey is first made of the pioneer work in the use of radio telemetry and solar aspect recording devices for measuring yaw. Then follow sections containing descriptions of the basic principles of the new system, the apparatus involved, the present method of reducing the results and notes on accuracy. In conclusion possibilities of improving and extending the technique are discussed. The deduction of mathematical formulae and the detailed description of some circuits have been relegated to appendices. No attempt is made here to analyse results so far obtained; this has been done by H.G. Haden in a separate report (3).

BRIEF SURVEY OF PREVIOUS METHODS OF MEASURING YAW EMPLOYING RADIO TELEMETRY AND SOLAR ASPECT RECORDING DEVICES

5. In 1944 A.F.H. Thomson (4) proposed that the polar radiation of an axially excited shell should be used to measure yaw by utilising the fact that the strength of the signal is proportional to $\sin \theta$, where θ is the angle between the axis of the shell and the direction of radiation. A receiving system polarised in either the vertical or horizontal plane would thus receive signals whose strength would be

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1. R.H.Fowler, E.G.Gallop, C.H.N.Lock and H.W.Richmond - The Aerodynamics of a Spinning Shell, Phil. Trans. Roy. Soc. Vol. CC XXI, Series A, 1920.
 2. D. Cooke - R.A.R.D.E. Unpublished work.
 3. H.G.Haden - Yaw measurement analysis, R.A.R.D.E. Memorandum 54/64.
 4. O.B. Proc. Q 2,555.

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related to the angle between the line from shell to receiver and the axis of the shell projected into either the vertical or horizontal plane. Knowledge of the actual trajectory was then required to deduce the component of yaw in the preferred plane. Practical experiments employing this concept were carried out at the Canadian Armament Research and Development Establishment (5). During these experiments it was found that the received signal was modulated by the spin frequency. This happened because the radio axis was invariably not coincident with the spin axis. Thus the spin history of the projectile could also be determined. Some of the disadvantages of this system are that,

- (i) the calculation of the yaw involves the measurement of an amplitude which is not only dependent on the yaw but also on the characteristics of the transmitting and receiving systems and their distance apart,
- (ii) the direction of the yaw is not determinable,
- (iii) it is only sufficiently sensitive over restricted arcs of the trajectory,
- (iv) it is not suitable for high angle fire,
- (v) the extraction of data is a lengthy process,
- (vi) knowledge of the trajectory is required.

It will be shown that all these disadvantages, except the last, have been eliminated by the method to be described.

6. The use of the direction of the sun's rays or rays from other external sources as a reference against which to determine the direction of the axis of a spinning projectile has a somewhat longer history. It is reputed to have been first used by the Russians during the first world war (6). A piece of sensitised paper was fastened to one internal wall of the shell cavity and a pinhole drilled in the wall diametrically opposite. For each revolution of the fired shell the sun's image swept across the paper, the excursion in one direction or the other depending on the orientation of the shell axis. On recovery of the shell after a short, flat trajectory, the limits of the traces indicated the maximum yaw. A similar technique, known as the Cambric method, was used in this country by R.J.B. Bolitho (7). The principle of this method was to fire a projectile, with a lens in the nose and sensitised paper fixed in a plane perpendicular to the principal axis, towards a system of fixed light sources at night or in a tunnel. The paths traced out by the photographic images of the light sources on the film were then used to determine the initial motion of the projectile. The system was refined by intermittently cutting off one light source at known regular intervals, thus providing the record with a time scale. Even so the evaluation of the record was a skilled and somewhat lengthy task.

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- 5. C.C.Gotlieb, P.E.Pashler and M.Rubinoff - A Radio Method of Studying the Yaw of Shells, Canadian Journal of Research, Vol. 26, Sec. A, Feb. 1948, p.p. 167-198.
 - 6. Field Testing of Rockets, California Institute of Technology, Pasadena, California, 1946.
 - 7. O.B. Proc. Q 1,935, 21 Feb. 1944.

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7. A significant improvement in the simplicity of the record was brought about in the U.S. by a suggestion of W.R. Smythe that led to the solar yaw camera (6). The pinhole was made in the side wall of the projectile, in this case a spinning rocket, and the excursions of the sun's image recorded on a film moving behind a narrow slit. The energy required for spooling the film was obtained from the differential spin of the rocket and a free flywheel. This ingenious system was very successful in recording the yaw of rockets over relatively long periods of time. It was not, so far as is known, used for gun projectiles, probably because of the difficulty of designing a film spooling mechanism capable of withstanding the much higher accelerations involved.
8. The major disadvantage of the solar yaw cameras so far described is that the record is only available when the projectile has been recovered. In the last system described the time scale is not directly obtainable but has to be derived from the total number of revolutions of the rocket during its time of flight and an assumed law of spin rate decay. Also the time over which a recording can be made is limited to the time that a sufficient difference exists between the spin of fly-wheel and rocket.
9. This survey is concluded with a reference to another, more recent development in the U.S. the Solar Aspect Telemeter (8), (9). It is used to investigate the rotatory motion of free falling bodies. A number of photosensitive elements with non-intersecting fields of view are disposed about the body in which is also incorporated a radio transmitter. Sunlight falling on any one of the elements causes the transmitter frequency to be modulated with a frequency associated with that particular element. The values of successively received frequencies thus give an indication of the rotatory motion with respect to the solar rays. With its technique of telemetering the outputs of photoelectric transducers this method shows probably the closest resemblance to the new system, described in the following sections.

BASIC PRINCIPLES OF THE SYSTEM

10. The basic construction of the angle sensing element is shown diagrammatically in Fig. 1. The projectile with circular cross-section APB has been drawn, for the sake of convenience, with its principal axis in the y-axis and is assumed to be spinning positively about that axis. A pinhole P in the wall of the projectile lies in the xz-plane. In a diametric plane perpendicular to OP are mounted symmetrically in the shape of a V two narrow strips of a photo-voltaic material. To illustrate the action, a solar ray SS' is shown parallel to the xy-plane and at an angle α to the y-axis (and hence also to the projectile axis). There is, of course, a parallel continuum of such rays, so that during each revolution of the projectile the solar image will sweep first across one arm of the V and then the other, thereby giving rise to two voltage pulses, provided α is within certain limits.

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8. T.Rasch - An improved Solar Aspect Telemeter Circuit, CWL Tech. Memo 30-21, Jan. 1957.
9. T.R.Paulson - Application of Transistors to Aspect Determination of a Free Falling Body, Symposium on the Application of Transistors to Military Electronic Equipment, Mon. 500-53, Nov. 1953.

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11. The complete train of such pulse pairs produced during the flight of the projectile is transmitted to a ground station where it is continuously recorded. The angle α can then be derived for all points of the trajectory from the time interval between the two pulses of a pair, the frequency of the occurrence of pulse pairs, the dimensions of the V and its position relative to the pinhole.

12. The experimental information obtained from the system is in itself not sufficient to measure actual yaw. Additional information is needed regarding the angle between velocity vector and solar ray at all points of the trajectory. For this purpose a computed trajectory is probably accurate enough, but in some cases it may be necessary to track the projectile simultaneously with radar.

APPARATUS

13. The whole apparatus consists of the yaw sonde in the shell and the receiving and recording equipment on the ground.

The yaw sonde

14. The yaw sonde comprising V-cell, amplifier, oscillator and energiser is accommodated in the body and nose of a shell fuse, (Fig. 2) which is attached to a shell body containing a hole of about 0.050 in. diameter in its wall (Fig. 3). Care has been taken to keep the masses and their distribution close to those of the service fuse and to protect the components against the high acceleration on firing. It was fortunate that most of the components - oscillator, energiser and amplifier housing - were already available and well tested in connection with the work on VT-fuses by B3/R.A.R.D.E.

The V-cell

15. The V-cell is made by cutting an equilateral triangle of 20 mm side from a standard circular Ferranti MS 11B Silicon cell of 1 inch diameter and masking all but two 1 mm wide edges with a layer of nickel. It is embedded in a circular flat disc of clear polyester resin, mounted axially in the threaded lateral bore of a stepped cylindrical Perspex housing with a cushioning layer of Silicon Rubber and secured by two locking rings. The output leads of the cell are connected to two concentric contacts on top of the housing. Rotation of the housing is prevented by a keyway, and the set back is taken up by a plug screwed in the fuse body.

16. The V-cell complete with housing was drop tested up to 16,000 g, and the transparent Perspex housing allowed very detailed inspection for any signs of cracking or dislocation, which were in fact absent. The assembly also withstood spinning tests up to 420 r.p.s. and was finally dynamically balanced by suitable choice of height of the locking rings.

17. The voltage produced by the cell with bright sunlight on the pinhole is about 20 mV across a working resistance of 470 Ohms.

The yaw sonde amplifier and oscillator

18. This system uses a standard VT fuse oscillator of about 200 Mc/s, a frequency which has been found to produce the most favourable radiation pattern of the shell as a whole. The oscillator consists of valve V₁, condensor C7, coils L₁, L₂, L₃ and an aerial (Fig. 4), all housed in the nose of the fuse, the aerial

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radiating through a plastic cover. It is modulated by anode voltage variation of valve V_1 from the amplified photocell signal. Although this method does not produce pure FM as required by the receivers - the modulation is about 60% FM and 40% AM - it is adequate for the purpose. The modulating voltage variation is provided by resistor R_2 which is the common anode resistance of the oscillator valve V_1 and the modulator valve V_2 . Between this modulator valve and the V-cell there is a two stage wide-band amplifier with RC-coupling, which provides a gain of about 100 between 100 c/s and 100 kc/s, so that the photocell signals appear as grid pulses of about 2 V at the modulator valve. The bandwidth is sufficient to give good reproduction of the V-cell pulses with the geometrical dimensions and spin rates used so far.

19. The amplifier with its two valves V_3 and V_4 and all its resistors and capacitors is built into the existing VT fuse amplifier housing of polythene, which is then potted in Alkathene polymer and firmly located in the rear compartment of the fuse nose.

The yaw sonde energiser

20. Power for the amplifier and oscillator is supplied by a standard VT-fuse energiser MX9R housed in a metal container which holds it rigidly in the fuse body forward of the V-cell housing. It provides three different voltages of +90 V, +1.5 V and -6 V, and as it is situated between V-cell and amplifier it also contains a two wire path for the photoelectric pulses to the amplifier input. The energiser is a wet battery which becomes operative on firing when a plastic container is broken, the electrolyte forced out of it and spread between the plates by centrifugal force.

21. Practical firings have shown that with this system of power supply and thermionic valve circuits the oscillator is fully operative after an average time of 0.4 s from shot exit. With a shell fired at 1500 ft/s the first 600 ft of trajectory can therefore not be measured.

Receiving equipment

22. The requirements for the receiver are mainly, that it should accept the incoming pulse position modulated carrier of nominally 200 Mc/s and reconstitute the information impressed on it by the amplifier-modulator system in the projectile as truly as possible. In the present practical case this means that it must be tunable from about 190 to 220 Mc/s to allow for the manufacturing tolerances of the oscillators. In the IF and output stages it should have a bandwidth from 100 c/s to 100 kc/s to match the frequency response of the sonde amplifier, and an automatic frequency control should allow FM-demodulation over an RF-band of ± 500 kc/s as the carrier frequency is known to shift from its nominal value due to the acceleration forces on firing and also to drift during flight, possibly under the influence of changing ambient conditions.

23. A receiver which meets all these requirements has so far not been available for trials and these had to be carried out with commercial equipment which in one or other respect was not fully suitable. In the first trials an Eddystone receiver was used which, when modified to feed the signal direct from the FM discriminator, had a modulation bandwidth of only 50 kc/s. Although tunable over a wide RF-range, the tuning to the shifting and drifting carrier had to be done manually which was not easy, especially in unfavourable weather conditions, when the modulation signal was disturbed by clouds.

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24. A Nems Clarke Receiver Type 1670-F with a modulation bandwidth of ± 500 kc/s and AFC over this range was a considerable improvement. It has adequate sensitivity over a tunable RF range from 70 to 220 Mc/s, but the signal suffers from excessive noise as the overall bandwidth is 5 times too great. Valuable information has however been obtained with this receiver regarding frequency shift and drift of the carrier by monitoring the AFC error voltage, and the experiences with the two receivers were used to draw up more precise requirements.

These are expected to be met by a receiver which is now available for trials. It is a standard commercial Vitro Electronics Receiver Type R-1037A, tunable from 190-230 Mc/s which has plug-in IF-modules with AFC offering a choice of either 400 kc/s or 2.4 Mc/s bandwidth. A switchable final output stage with filter circuits allows selection of the required bandwidth of 100 kc/s.

25. An aerial of the multi-element 'Yagi' unidirectional type positioned some 4000 yd forward of the gun and about 40° off line to make reasonably good use of the radiation pattern of the shell gives adequate reception up to 13000 yd if some form of aerial tracking is provided. In the firings carried out so far an improvised method of manual tracking has proved quite successful. The aerial is fixed to a light AA mounting and two operators on bearing and elevation work to a programme determined beforehand from a simple scale model containing the calculated trajectory and the position of the aerial relative to the gun.

Recording equipment

26. The pulses from the FM discriminator of the receiver are recorded in different ways against time by presenting them in suitable form on an oscilloscope and producing a trace on film or paper. Such records can either be obtained directly during the actual flight of the shell or from a magnetic tape on which the pulses have been stored via a wide band amplifier.

27. At present the best method to obtain a useful "compressed" record of the history of the angle α between shell axis and solar ray over the whole trajectory appears to be one in which the pulses are not recorded in their original form, but are used to time locally generated short square pulses by triggering them whenever the trailing edges of the original pulses have fallen to a predetermined fraction of the maximum amplitude. In this way inaccuracies due to varying pulse amplitudes are minimised, and at the same time a better pulse shape is obtained for recording purposes.

28. Figure 5 shows the block diagram of such a pulse recording unit. The pulses (a) from the receiver or magnetic tape are used in the trigger pulse generator to produce the accurate timing pulses (b), which are then separated in the pulse separator, so that all the first pulses of the pulse pairs appear at one output (c) and all the second pulses at the other (d). The separated pulses are fed into two identical output pulse generators where they trigger square wave pulses (e) and (f) of adjustable width. These pulses then pass to a diode circuit, which is so arranged that one of two following RC differentiating members receives only the pulses (e), whereas the other receives the pulses (g), a superposition of (e) and (f). After differentiation the final output pulses (h) and (i) appear at two separate terminals from which they can be taken for simultaneous beam brightening of two separate cathode ray oscillographs in the case of direct recording from the receiver, or they can be switched alternatively to the beam brightening circuit of one single oscillograph in the case of recording from magnetic tape. This latter case has been assumed in Figure 5. The sweep of the oscillograph is triggered by the pulses (h),

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and with suitable choice of the time base speed two bright spots can be made to appear on the screen (the first always being fixed at the beginning of the sweep), which according to the switching position represent either the first pulses or both pulses of the pulse pairs.

29. If the screen is photographed with an oscilloscope camera in which the film or paper moves at right angles to the direction of the sweep, records of two different types are obtained as shown in Fig. 6. Both contain two lines made up by a succession of dots; one line is parallel to the edge of the film, the other varies in distance from the first. In one type of record this distance represents the time between a pair of pulses produced by the V-cell and in the other the spin period. If the sweep of the oscillograph is calibrated by switching a square wave pulse generator with variable pulse repetition of known value on to the oscilloscope these times can be measured and used to calculate angle α . This method of recording has the advantage that even without any calculation it permits easy visual appreciation of the general pattern of the yawing motion and the deceleration of spin.

A more detailed explanation of the recording unit is given in Appendix B.

30. Sometimes other recording methods can be used with advantage. If for instance a part of the trajectory of special interest is to be analysed with greater time resolution or the shape of the pulses from the receiver to be studied in detail, the pulses may be fed to an oscilloscope with a static light spot which is then photographed on film running at high speed at right angles to the direction of the excursions produced by the pulses.

31. All recording instruments are provided with timing and synchronisation marks to relate their readings to the trajectory of the projectile. Synchronisation is achieved by a multi-channel galvo-recorder with built-in time base which receives by radio link a shot ejection signal and also records the strength of the received signal, its frequency shift and drift during flight and the ground wind speed. The galvo-recorder has also been used as a quick look facility providing immediate records of the V-cell pulses with a method in which the pulse times are converted in an analogue system to voltage amplitudes by charging a capacitor linearly via a constant current generator. The system used had been developed by C. Riddle, F1/R.A.R.D.E. for missile tracking purposes (10).

DERIVATION OF YAW COMPONENT

32. The experimentally measured angle α between projectile axis and solar ray is given by the expression

$$\cot \alpha = \frac{c}{r} \cos \frac{Nt}{2} - \cot \phi \sin \frac{Nt}{2} \dots\dots (1)$$

where c , r and ϕ are constants of the V-cell/pinhole assembly as shown in Fig. 1
 t is the time interval between the two pulses produced in one spin period (in seconds)
 N is the angular velocity of the projectile about its principal axis (in radians per second).

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In the deduction of this equation which is shown in Appendix "A" it has been assumed that there is no appreciable yawing motion during a single revolution of the projectile. This assumption is probably justified in most practical cases; it will be discussed later in the section on accuracy.

33. The angle α can be used to determine the yaw component in a reference plane defined by the solar ray passing through the trajectory and the tangent to the trajectory (Fig. 7). As shown in Appendix "A", this component δ_2 is given by

$$\cos (\psi - \delta_2) = \frac{\cos \alpha}{\cos \delta_1} \dots\dots (2)$$

where ψ is the angle between solar ray and the tangent to the trajectory
 δ_1 is the component of yaw in the plane at right angles to the reference plane which passes through the projectile axis.

For a stable projectile the yaw is usually small, so that it will generally be admissible to equate $\cos \delta_1$ to 1 and obtain δ_2 from the simple equation

$$\delta_2 = \psi - \alpha \dots\dots (3)$$

Hence the projection of the yaw in the reference plane can be determined, when in addition to the angle α measured by the system the angle ψ is calculated from the known attitude of the sun and the direction of the tangent to the trajectory for each point under consideration.

ACCURACY

34. The accuracy with which the yaw component δ_2 can be determined depends according to equation (2) on the accuracy of α and ψ .

35. From equation (1) it can be seen that errors in α can have two main causes:

- (a) errors in the experimentally determined values of N and t
- (b) departures from the nominal values of c , r and ϕ to which should be added
- (c) errors in the inner orientation of the V-cell/pinhole assembly.

If the V-cell can be assumed to remain in its original position throughout the whole flight, the errors due to (b) and (c) will be constant for any particular round fired and thus introduce a systematic error into the calculated values of α . The reduction of this error to a minimum is an engineering problem to which not much attention has been given so far, but it seems that even with the strictest possible manufacturing tolerances there may well remain a bias in α of about 30 minutes. Aerodynamically speaking, this error will affect the determination of equilibrium yaw. It can, of course, be eliminated by a completely different approach, namely by dispensing with accurate manufacture and assembly and calibrating instead each individual projectile in a test rig. Such a test would be desirable in any case to examine the effects of simulated set back forces.

36. Errors in the amplitude of yaw about the equilibrium will arise from errors in the determination of N and t . With the present design in the projectile chosen as a test vehicle these errors are estimated to give an error of about 0.1 degree in α . This figure seems to be confirmed by the scatter of the points in yaw histories so far worked out.

37. If the projectile is yawing in the reference plane, α will be changing whilst being measured. With the present configuration the change in α during the scanning time would be less than 0.1° if the yawing frequency was 15 c/s with an amplitude of 2° in the reference plane. The effect of yawing in a perpendicular plane would be considerably less. In any case the value obtained for α would be a mean value, and as such high yawing rates are only rarely encountered, the effect of yawing can generally be ignored.

38. The accuracy of ψ , the angle between solar ray and tangent to the trajectory, depends on the accuracy with which these two directions can be determined. Azimuth and elevation of the sun at any time and at any location can be obtained from the Nautical Almanac (11) and the appropriate Sight Reduction Table (12). The process generally involves some rather laborious interpolation, but it will be assumed that the information so obtained is free of error.

38. The values taken for the direction of the tangent to the trajectory can be obtained either by tracking the shell in some way, or, if its ballistic characteristics and other relevant data are known, by computing a trajectory. The effects of errors in this information on the accuracy of ψ will now be examined.

40. Assume in the first place a plane trajectory and choose a set of axes so that the trajectory lies in the yz -plane. Let the tangent to the trajectory make an angle θ with the y -axis and let the direction cosines of the solar rays be l_s, m_s, n_s .

Then ψ is given by

$$\cos \psi = m_s \cos \theta + n_s \sin \theta \dots\dots (4)$$

By differentiation (with m_s and n_s constant) we have

$$\begin{aligned} -\sin \psi \delta \psi &= -m_s \sin \theta \delta \theta + n_s \cos \theta \delta \theta \\ \delta \psi &= \frac{m_s \sin \theta \delta \theta - n_s \cos \theta \delta \theta}{\sqrt{1 - (m_s \cos \theta + n_s \sin \theta)^2}} \dots\dots (5) \end{aligned}$$

i.e.

$$\delta \psi = 0 \text{ if}$$

$$(i) \quad \delta \theta = 0$$

$$(ii) \quad m_s \sin \theta = n_s \cos \theta$$

$$(iii) \quad m_s = n_s = 0$$

11. The Nautical Almanac, London: Her Majesty's Stationery Office.

12. Sight Reduction Tables for Air Navigation, London: Her Majesty's Stationery Office.

(i) and (ii) are of no practical interest.

(iii) shows that if conditions are chosen so that the sun's rays are perpendicular to the plane of the trajectory, ψ will be constant and equal to 90° and not affected by errors in θ .

41. With a trajectory in a perpendicular plane this condition is only possible at sunrise or sunset, and these are therefore the optimum occasions for carrying out experiments. Moreover, since under these conditions ψ is constant ($= 90^\circ$) the whole range of the angle sensitive device can be utilised for recording yaw. With the pinhole-V-cell assembly generally used so far, the range in α extends approximately from 77° to 103° , so that a yaw component of up to $\pm 13^\circ$ can be measured. It is, however, usually desirable to fire more than two rounds a day, and for practical reasons a shoot is generally arranged to begin towards sunset when the sun is at an elevation of about 10 degrees. This case will therefore be considered as being of special interest.

42. By firing in a plane at right angles to the projection of the sun's rays in the xy-plane we have

$$\text{from (4)} \quad \cos \psi = \cos 80^\circ \sin \theta \quad \dots\dots\dots (6)$$

$$\text{from (5)} \quad \delta\psi = - \frac{\cos 80^\circ \cos \theta \delta\theta}{\sqrt{1 - (\cos 80^\circ \sin \theta)^2}} \quad \dots\dots\dots (7)$$

$$\text{since} \quad m_s = 0.$$

From equation (6) the change in ψ during the course of a trajectory can be found. If for example

at launch $\theta = 45^\circ$
and at impact $\theta = -50^\circ$
 ψ varies from 82.3° to 97.6° and the range available
for yaw recording is reduced accordingly to about $\pm 5^\circ$.

From equation (7) follows for constant $\delta\theta$, that $\delta\psi$ is a maximum when $\cos \theta = 1$ (i.e. $\theta = 0$ at the vertex), and in the case considered

$$\delta\psi = -0.17 \delta\theta.$$

43. It remains to arrive at an estimate of $\delta\theta$, the error in the angle that the tangent to the trajectory makes with the line of fire (the y-axis). As previously mentioned there are two methods of plotting a trajectory: by tracking an actual projectile or by computation. There are now comprehensive facilities in existence which can plot trajectories of radar tracked projectiles down to medium calibre with a high degree of accuracy, and $\delta\theta$ would probably be of the order of $0.3^\circ - 0.5^\circ$, so that under the conditions assumed above $\delta\psi$ should not exceed 0.1° .

44. These tracking facilities are, however, only available as fixed range installations, and it will not always be easy to accommodate a yaw trial on these ranges. It will therefore probably in most case be necessary to use computed trajectories, possibly with occasional checks by tracking. It is at present not known what accuracy in θ can be achieved with this method, but there is reason to believe that in the case of a medium calibre projectile as that with which the

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development work on this method of yaw measurement has been carried out, it may be of the order of a degree or two in some parts of the trajectory. This would introduce a systematic error in ψ of perhaps up to 0.5° .

45. So far it has been assumed that the trajectory is planar, but of course, spin stabilised projectiles have a drift and in addition cross winds deflect the missile from the original plane of fire. Any such deviations change the value of ψ which, if not corrected, will introduce an error in δ_2 . When using tracked trajectories this error does not arise, and in the case of computed trajectories it will depend on the accuracy with which the effects of wind and drift on the velocity vector can be estimated.

FURTHER DEVELOPMENTS

46. With the present system a test programme of 79 fired 105 mm shells has so far been carried out: many of these rounds had to be fired under unfavourable weather conditions. It has been shown that the system is very reliable in operation and yields results, of which at this stage it can at least be said, that they give a very clear and informative picture of the yaw and spin over practically the whole trajectory and show great promise of accurate measurement.

47. There are several possibilities of modifying the system with a view to improving its performance in general or for special applications.

48. One obvious shortcoming of the present system is, that the sonde with thermionic valves becomes only fully operative 0.4 seconds after shot ejection, so that the initial yaw and its damping cannot be fully observed. This can be overcome by using a transistorised sonde, which has also the advantage of greater compactness, allowing the whole sonde including pinhole to be accommodated in the nose of the fuse and thus obviating the necessity of drilling a hole in the shell body.

49. Repositioning of the optical system into the fuse nose with a view to avoid a hole in the shell body is also envisaged with the valve sonde by modifying the design so that the amplifier and the V-cell housing change places.

50. On the recording side it might in certain cases be preferable to have the data not as photographic records but in digital form. This would especially apply when whole series of trajectories have to be thoroughly evaluated and the time factor becomes important.

51. With regard to evaluation, it may also be found convenient to choose other shapes for the solar cell. An N-shaped cell leads for instance to a somewhat simpler formula for the angle α . Also an additional pinhole might be used to extend the measuring range.

52. It is of course possible to reverse the arrangement of pinhole and solar cell, i.e. one could use a point-sized photocell on the projectile axis and a V- or N-shaped mask instead of the pinhole, which might have practical advantages. This arrangement would for instance make it easier to achieve greater sensitivity of the optical system, if that of the present assembly, which is mainly limited by the distance between pinhole and solar cell should prove to be insufficient for certain applications. The small photocell could probably be more easily placed at a greater distance from the mask in the wall than it would be possible to find a

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suitable position for the relatively large solar cell further away from the pinhole. It might even be possible to make the distance adjustable so that the sensitivity of the optical system could be changed during a trial to obtain the most suitable measuring range for each individual measuring problem.

ACKNOWLEDGMENTS

53. This work is based on a concept of D. Cooke, and was actively directed by him until his transfer to the A3 Branch. He also suggested some of the possible modifications and extensions of the system which are described in the previous section.

54. Appreciation is expressed for the co-operation of Chief Superintendent of Ranges, Superintendent Proof and Experimental Establishment Pendine and Headquarters Libya and Malta in providing range facilities and staff for the trials. Most valuable help was received from G.R.R. Bray and G.R. Siekmann of R.A.R.D.E., who advised on VT fuses and made components and test gear available.

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APPENDIX A

DERIVATION OF α AND δ_2

Derivation of the angle α between projectile axis and solar ray

1. Fig. 1 shows a diagrammatic representation of the V-cell and pinhole assembly. A system of axes with origin O is chosen so that the y-axis coincides with the principal axis of the missile, the xz-plane coincides with the plane APB, which contains the pinhole P and is perpendicular to the principal axis of the projectile and the yx-plane is parallel to the solar rays. Two thin strips of photo-voltaic material, DE and EF are shown mounted in the diametric plane AEB, which is perpendicular to the radius OP ($= r$) through the pinhole. The co-ordinates of the point E, at the corner of the V are (0, -C, 0) and the semi-angle of the V is ϕ as shown.

2. The projectile is supposed to spin in a clockwise direction about its principal axis (the y-axis) with an angular velocity N radians per second. In Fig. 1 the solar ray SS' passing through the pinhole P is shown impinging on the upper arm of the V, when OP makes an angle $-\beta$ with the x-axis. A parallel solar ray would similarly strike the other arm of the V when OP made an angle $+\beta$ with the x-axis. The solar ray makes an angle α with the y-axis. This is the angle which it is required to obtain in terms of c, r, ϕ and β .

3. The equation of the solar ray is

$$\frac{x - r \cos \beta}{\sin \alpha} = \frac{y}{\cos \alpha} = \frac{z + r \sin \beta}{0} = f \text{ (say) } \dots\dots (1)$$

The equation of the upper arm of the V is

$$\frac{x}{\sin \phi \sin \beta} = \frac{y + c}{\cos \phi} = \frac{z}{\sin \phi \cos \beta} = g \text{ (say) } \dots\dots (2)$$

For intersection we have from (1) and (2):

$$f \sin \alpha + r \cos \beta = g \sin \phi \sin \beta$$

$$f \cos \alpha = g \cos \phi - c$$

$$-r \sin \beta = g \sin \phi \cos \beta$$

The eliminant for f and g is

$$\begin{vmatrix} \sin \alpha & \sin \phi \sin \beta & r \cos \beta \\ \cos \alpha & \cos \phi & c \\ 0 & \sin \phi \cos \beta & -r \sin \beta \end{vmatrix} = 0$$

which gives

$$\sin \alpha [r \sin \beta \cos \phi - c \sin \phi \cos \beta] = -r \sin \phi \cos \alpha$$

and
$$\cot \alpha = \frac{c}{r} \cos \beta - \cot \phi \sin \beta.$$

Now if t is the time interval in seconds between two voltage pulses which occur when the sun's rays strike the arms of the V successively, and s is the frequency with which the sun's rays impinge on one or the other of the arms, then

$$2\beta = 2\pi s t = Nt$$

where N is the spin rate in radians per second.

Hence

$$\cot \alpha = \frac{c}{r} \cos \frac{Nt}{2} - \cot \phi \sin \frac{Nt}{2}$$

Derivation of δ_2 , the component of yaw in the plane defined by the velocity vector of the c.g. of the projectile and the position vector of the sun

4. In Fig. 7 rectangular axes are chosen so that the y-axis coincides with the velocity vector of the projectile and the x-axis lies in the plane defined by the velocity vector of the projectile and the position vector of the sun. The projection of the projectile axis in the xy-plane makes an angle δ_2 with the y-axis, and the projectile axis makes an angle δ_1 with its projection in the xy-plane.

5. The solar ray (in the xy-plane) makes an angle ψ with the y-axis and an angle α with the projectile axis.

The direction cosines of the projectile axis are

$$\cos \delta_1 \sin \delta_2$$

$$\cos \delta_1 \cos \delta_2 \quad (= \cos \delta, \text{ where } \delta \text{ is the total yaw})$$

$$\sin \delta_1$$

The direction cosines of the solar ray are

$$\sin \psi$$

$$\cos \psi$$

$$0$$

Thus angle α between solar ray and projectile axis is given by

$$\begin{aligned} \cos \alpha &= \cos \delta_1 \sin \delta_2 \sin \psi + \cos \delta_1 \cos \delta_2 \cos \psi \dots\dots\dots (3) \\ &= \cos \delta_1 \cos (\psi - \delta_2) \end{aligned}$$

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For small δ_1 we can approximate $\cos \delta_1 = 1$ and have

$$\delta_2 = \psi - \alpha$$

6. For large yaw the above expression may not be sufficiently accurate. If it can be reasonably assumed that conical yaw about the tangent to the trajectory is occurring, then δ_2 may be more accurately expressed.

With $\cos \delta_1 \cos \delta_2 = \cos \delta$

equation (3) can be written

$$\cos \alpha = \cos \delta (\cos \psi + \tan \delta_2 \sin \psi)$$

i.e.

$$\tan \delta_2 = \frac{\cos \alpha}{\cos \delta \sin \psi} - \cotan \psi$$

Where δ is taken as the maximum local value of δ_2 .

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APPENDIX B

PULSE UNIT FOR YAW TELEMETRY RECORDING

Purpose

1. The output signals of the receiver or the magnetic tape used in the yaw telemetry system described consist of trains of pulse pairs. The pulses are of a duration up to 50 microseconds, they have a rounded shape and vary widely in amplitude. These features make them unsuitable for direct measurement of time intervals between pulses. A pulse unit has therefore been developed which converts the original pulse train into a train of short pulses with constant shape. The unit consists of

- (a) a trigger pulse generator and amplifier
- (b) a monostable/bistable pulse separator
- (c) two output pulse generators, mixer and shapers.

Trigger pulse generator and amplifier (Fig. 8)

2. The output of the receiver is connected to one end of the input potentiometer RV1 and earth. The two condensers C_1 and C_2 are in series between the slider of RV1 and earth but separated by the diode Tr1. When the input pulse voltage is rising positively C_1 and C_2 become charged to voltages which are inversely proportional to the capacities of C_1 and C_2 , and the sum of these voltages is equal to the voltage at the slider of RV1. At the end of the pulse rise time C_1 and C_2 cease to be further charged and the diode Tr1, which now becomes reversely biased, separates them. When the input voltage starts to fall, the charges in C_1 and C_2 remain constant, since no current can flow through Tr1. However, as soon as the input voltage at the slider of RV1 has fallen by the voltage stored in C_1 , current flows from C_1 into the emitter-base diode of the trigger timing transistor Tr2 connected to it, which switches Tr2 on and discharges C_1 at the same time. Similarly, when the input voltage at the slider of RV1 has fallen to the voltage stored in C_2 , the latter begins to discharge via the diode Tr3. When the input voltage has dropped to zero, both C_1 and C_2 are in the discharged state.

3. The beginning of current flow from C_1 into Tr2 marks the point at which the input pulse voltage has fallen from its peak value by a percentage controlled by the values of C_1 and C_2 according to the formula

$$\% \text{ of fall} = \frac{100 C_1}{C_1 + C_2}$$

where C_1 and C_2 are the capacities of condensers C_1 and C_2 .

4. When Tr2 is switched on (at approximately 25% fall of input voltage taking constant error voltages into account) and base current flows, an amplified current flows in its collector circuit. The voltage drop developed across the collector resistance R1 is differentiated by condenser C3 and the base impedance of Tr4, R2 only serving to prevent the base of Tr4 from floating. The amplified waveform in the collector circuit of Tr4 is further differentiated and amplified by C4 and Tr5 and as a result a voltage pulse sharply rising in the positive direction is produced

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across R5. The pulse pairs produced here trigger the monostable/bistable pulse separator.

5. The accuracy with which the trigger pulse generator and amplifier circuit can determine the separation of pulses depends on the signal to noise ratio, on the characteristics of the diodes Tr1 and Tr3 and of the emitter-base diode part of Tr2 and on the leakage currents in the diodes Tr1 and Tr3 and in the base diode of Tr2. These factors are discussed in the following paragraphs 6-9.

6. Any noise superimposed on the signal raises or lowers the momentary resulting voltage above or below the voltage of the noise-free signal. This effect causes two kinds of errors in the timing of the trigger pulses. Firstly depending on the polarity of the noise at the peak of the received pulse it will increase or decrease the voltage stored in the condensers C_1 and C_2 (noise modulation of stored voltage). Secondly, depending on the polarity of the noise near the trigger level, it will cause this preset level to be reached earlier or later than with a noise-free pulse (noise modulation of triggering time). These errors can be minimised by two measures. The first is to reduce the amplitude and slope of the noise pulses by narrowing the receiver bandwidth with suitable filters without substantially changing the waveform of the main pulses. The second is to choose the ratio $C_1 : C_2$ so that the trigger level is set at a steep portion of the trailing edge of the pulse, thus reducing the triggering time modulation by the superimposed noise. The choice of the trigger level is however somewhat restricted by the fact that the two pulses of a pair will no longer be resolved if the level is set too low on the trailing edge and the second pulse begins to rise before the first has fallen to the triggering level. As a reasonable compromise triggering at 75% of the peak voltage has been chosen.

7. The forward threshold voltages of the diodes Tr1 and Tr3 and of the diode part of Tr2 introduce errors in the voltages to which C_1 and C_2 are charged and discharged. Although constant they give rise to an error in the trigger level by changing the ratio of the stored voltages in the condensers with varying input amplitude. The diode characteristics should therefore be such that current begins to rise steeply at as low a forward threshold voltage as possible. Tr2 should also have a relatively high gain for low base currents, and its collector current should begin to rise at a voltage as close as possible to zero base voltage.

8. The leakage currents in the diodes Tr1 and Tr3 and in the base diode of Tr2 should be low with reverse bias so that the condensers, particularly C_1 , are not discharged during the start of the fall.

9. For reasons of suitable characteristics the emitter-base diodes of transistors OC43 were chosen for Tr1 and Tr3 in preference to simple diodes, and similarly transistor OC84 was chosen for Tr2.

Monostable/bistable pulse separator (Fig. 8)

10. The pulse separator consists essentially of a pair of transistors (Tr6 and Tr7), which are P-N-P-N devices like silicon controlled rectifiers but have closely controlled characteristics. Tr6 and Tr7 are cross coupled and each can be triggered from the "off" to the "on" state by the pulses produced by Tr5 across R5.

11. When the -11 V supply is switched on, charging current begins to flow into C_5 through RV2, R8, R9, Tr8, Tr9 and the emitter gate diode of Tr7, which is thereby switched into the conducting or "on" state (Tr8 and Tr9 are needed to drop the

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saturation voltage of Tr6 below the trigger voltage of Tr7). Tr6 remains in the "off" state since the voltage at its gate does not rise in respect of its emitter when the -11 V supply is switched on, because Tr5 is not switched on. Current flows through Tr7 via the limiting resistance R10 into the base of Tr10, which is hereby switched on and shorts C5. Thus this quiescent state (Tr7 and Tr10 conducting) is maintained until the first positive going pulse of a pair is produced across R5 by Tr5.

12. The first pulse produced across R5 has no effect on Tr7 (which is already in the "on" state), but it triggers Tr6 into the "on" state. The collector voltage of Tr6 then drops from zero to within about 1.5 V of the -11 V H.T. line in about 1 microsecond. Some of this negative voltage drop is transmitted to the collector of Tr7 via C7 with the result that the voltage at the collector of Tr7 drops from about -9 V to a value more negative than the -11 V H.T. line. This drop switches Tr7 and Tr10 off and the current through Tr6 begins to charge C5. Charging proceeds (with a time constant controlled by the setting of the potentiometer RV2) until one of two things happen.

13. If no further trigger pulse appears across R5 in time, charging of C5 by Tr6 continues until the charging current falls below the holding current of Tr6 (about 4.5 mA). At this point Tr6 reverts to the "off" state and the voltage drop across RV2 and R8 disappears, producing a fast positive rise via R9, Tr8 and Tr9, which triggers Tr7 from the "off" to the "on" state. The collector current of Tr7 then flows into the base of Tr10 and switches it on. Tr10 in turn discharges C5 in a short time and restores the whole circuit to its quiescent state again. By adjustment of RV2 the time taken for this monostable type of operation can be varied from approximately 200 microseconds to 1 millisecond. R8 is included in case RV2 is inadvertently set to zero.

14. If, however, another trigger pulse appears across R5 whilst Tr6 is charging C5, this pulse will trigger Tr7 into the "on" state. The voltage drop at the collector of Tr7 then switches off Tr6 via C7 and also Tr10 so that the circuit is again in its quiescent state. In this case Tr6 and Tr7 operate as a bistable circuit.

15. Normally, two pulses will arrive and operate the circuit as a bistable one, but the complication of the monostable operation is necessary to ensure that the circuit will also return to the quiescent state if only one pulse arrives. This can for instance happen when one pulse of an incoming pair is of such low amplitude that it cannot trigger Tr6, or when the two pulses are so close together that only one pulse comes out of Tr5. In this case the quiescent state is reached after a time (controlled by the setting of RV2), which must always be longer than the longest expected separation between two pulses of a pair but shorter than the period between pulse pairs.

16. The negative going voltage drops at the collectors of Tr6 and Tr7 are differentiated by C9, R12 and C10, R14 respectively, and the low amplitude crosstalk via coupling condenser C7 is cut off by the two silicon diodes Tr11 and Tr12 in series with R13, and Tr13 and Tr14 in series with R15 respectively. At the output terminal 1 therefore a clean single pulse is produced, when a single input pulse or the first pulse of a pair has fallen by 25%, whereas a similar pulse appears at output terminal 2 either when the second pulse of a pair has fallen by 25%, or, in the case of only one input pulse, after the time interval set by RV2.

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Output pulse generators, mixer and shapers (Fig. 9)

17. The two identical pulse generators are triggered by the time separated output pulses appearing at the output terminals 1 and 2 of the pulse separator. As they operate in exactly the same way, only the upper generator will be described here.

18. The input pulse from output terminal 1 of the pulse separator is fed into the emitter follower stage Tr15, which switches on transistor Tr16 very hard. Condensor C11 in the collector circuit of Tr16 is connected to the base of the left hand transistor Tr19 of a long tailed pair. The voltage across this condensor reaches its quiescent value when the base current of Tr19 becomes equal to that through the constant current device Tr18-R20-C12. This quiescent voltage can be set by RV3, which supplies the base voltage for the right hand transistor Tr20 of the long tailed pair. The negative input pulse (through Tr15) causes Tr16 to charge condensor C11 towards zero volts. After the end of the input pulse the constant current from the collector of Tr18 begins to discharge C11 towards its quiescent voltage again.

19. Each input pulse thus initiates a single sawtooth, beginning with a rapid charge of C11 and followed by a linear discharge ramp the length of which can be adjusted by RV3. During the generation of the sawtooth Tr19 becomes cut off and consequently more current flows through Tr20. Most of this current flows into the base of Tr21, switching it on harder, thereby producing a negative going pulse equal in duration to the sawtooth. These pulses at the collector of Tr21 (and Tr41 in the lower generator) are then mixed and shaped.

20. The mixing circuit consists of the two diodes Tr22 and Tr42 and resistance R49. It combines the negative pulses from Tr21 and Tr41 across R49.

21. The shaping of the two outputs is achieved by differentiating them with different time constants. The longer pulse from output 1 can be used to trigger the recording oscilloscope and to brighten the beam for spin period recording, while the combined shorter pulses on output 2 are used when recording the separation of the pulses in the pulse pairs.

Accuracy

22. The accuracy of the complete circuit was measured with artificial test pulses. One, two or three square pulses were taken from a programmed generator with variable pulse separation and converted into positive going sinusoidal half-wave pulses of equal duration (approx. 35 μ s at half amplitude) but with individually adjustable amplitudes. These pulses were fed into the trigger pulse generator, and the separations of the input and output pulses were measured on an oscilloscope with dual trace plug-in preamplifier. Keeping the separation of the input pulses constant, a variation of the peak voltage of the first or second pulse from 1 to 8 V produced an error of the output pulse separation of 0.5 μ s. A reduction to 0.5 V increased the error to 1 μ s.

23. In practical firings it was found that the variation in the amplitudes of the two pulses of a pair was approximately 4:1 at most. With a minimum separation of 50 μ s between a pair of pulses the error would be less than 1% and correspondingly smaller for longer separation periods if the input voltage pulses are kept between 1 and 8 V by the potentiometer RV1 (Fig. 8).

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FIG. I

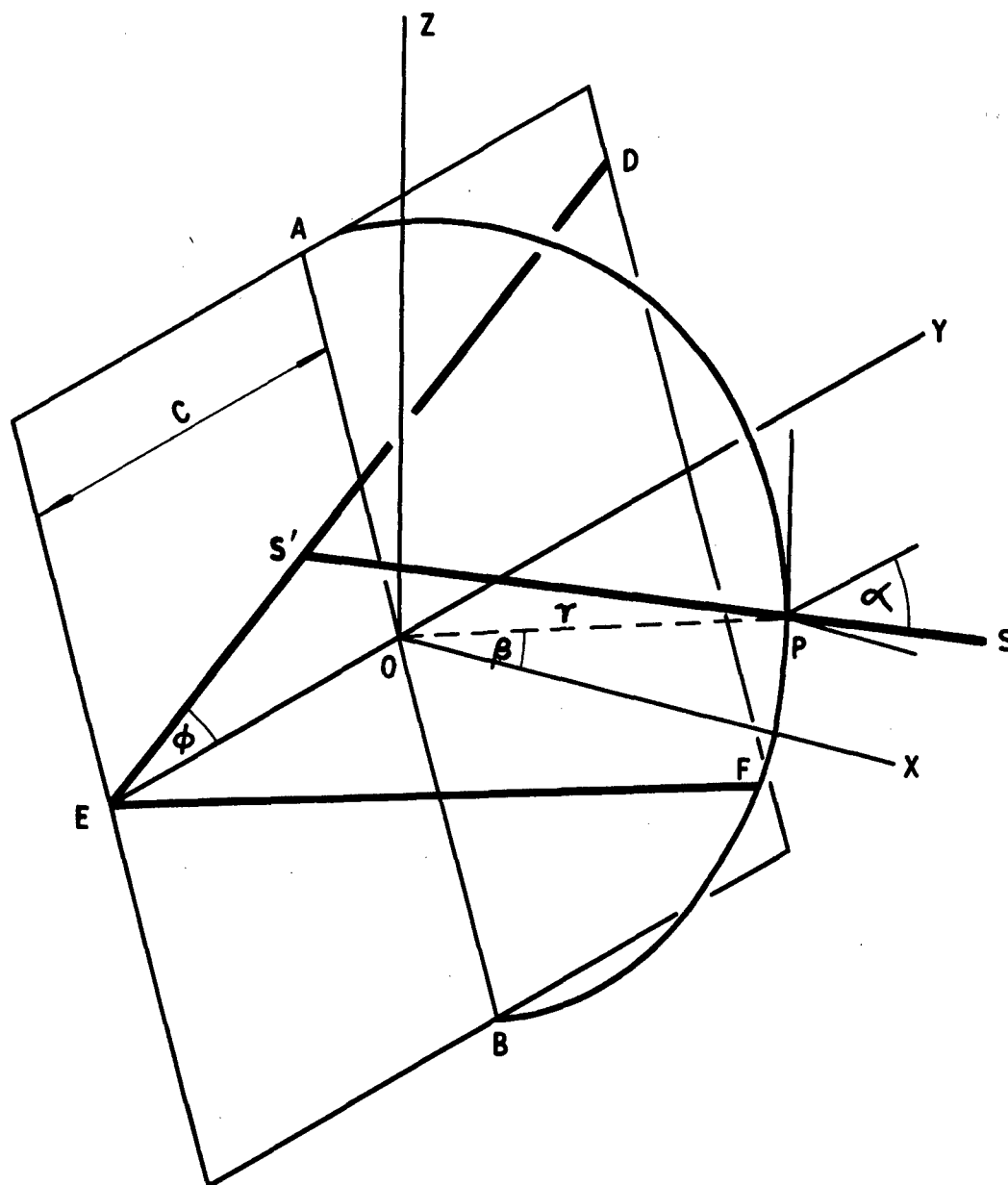


FIG. I PRINCIPLE OF V-CELL AND
PINHOLE ARRANGEMENT

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FIG. 2

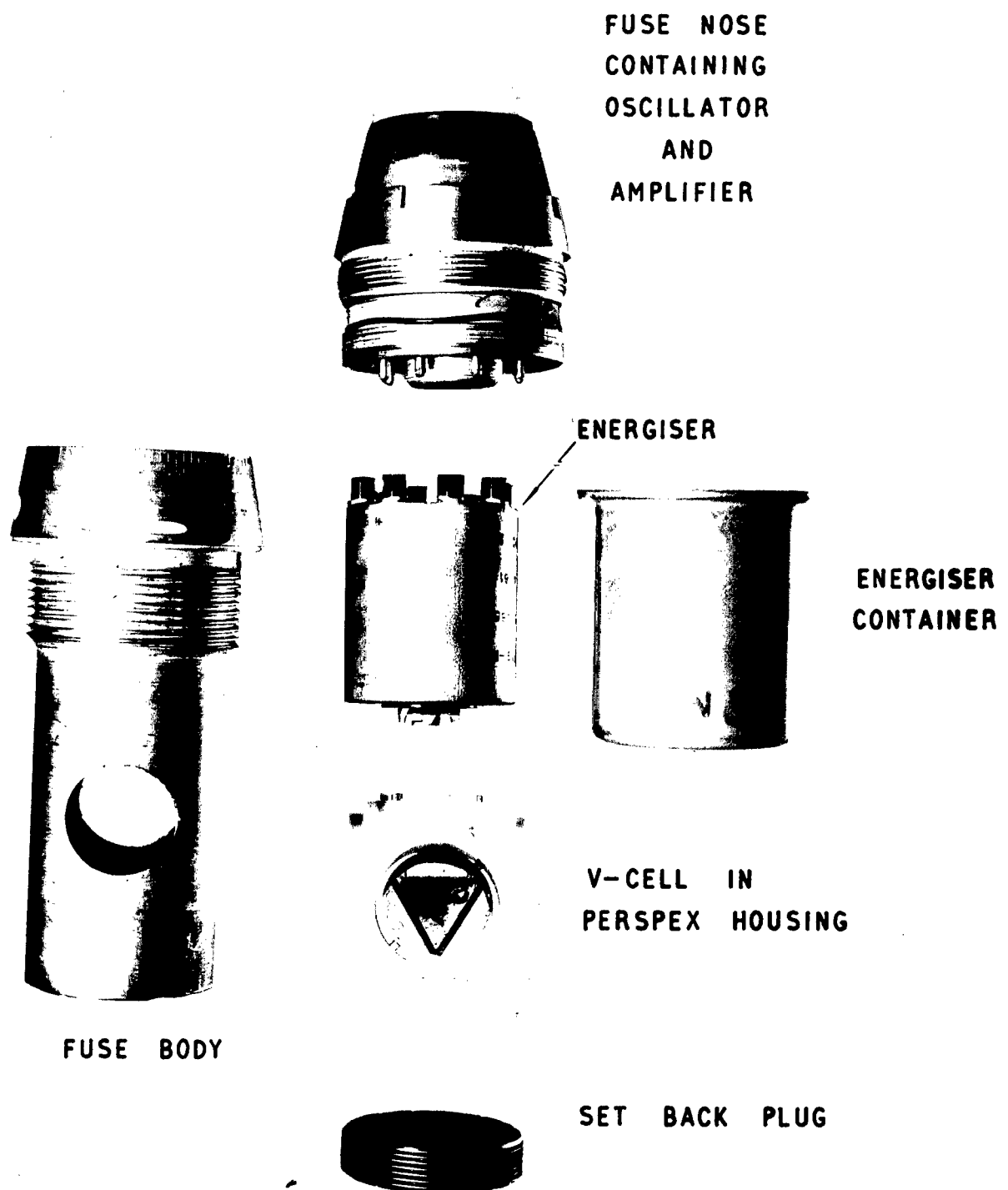


FIG. 2 YAW SONDE COMPONENTS

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FIG. 3

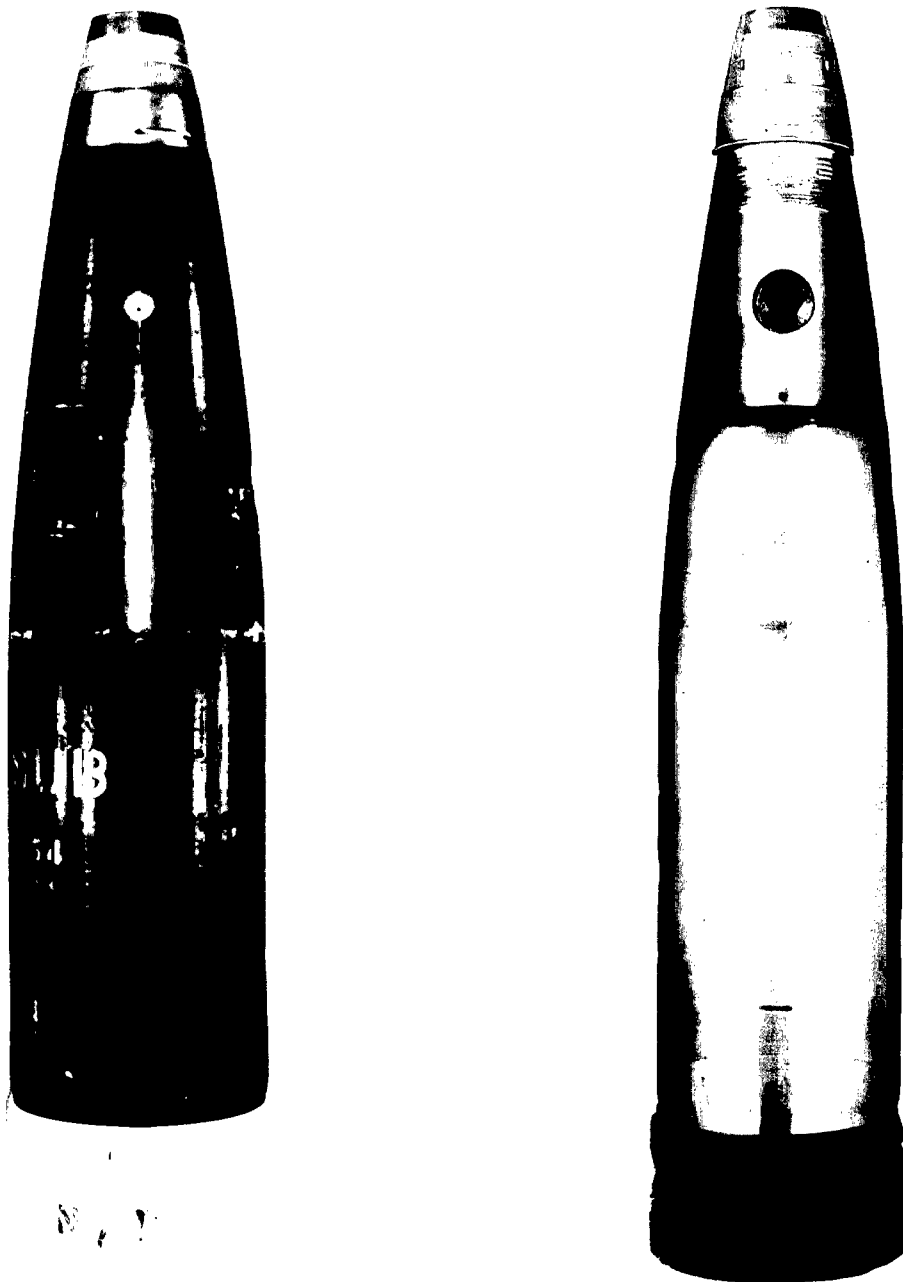


FIG. 3 SHELL WITH PINHOLE AND CUTAWAY VIEW OF SHELL
WITH YAW SONDE

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FIG. 4

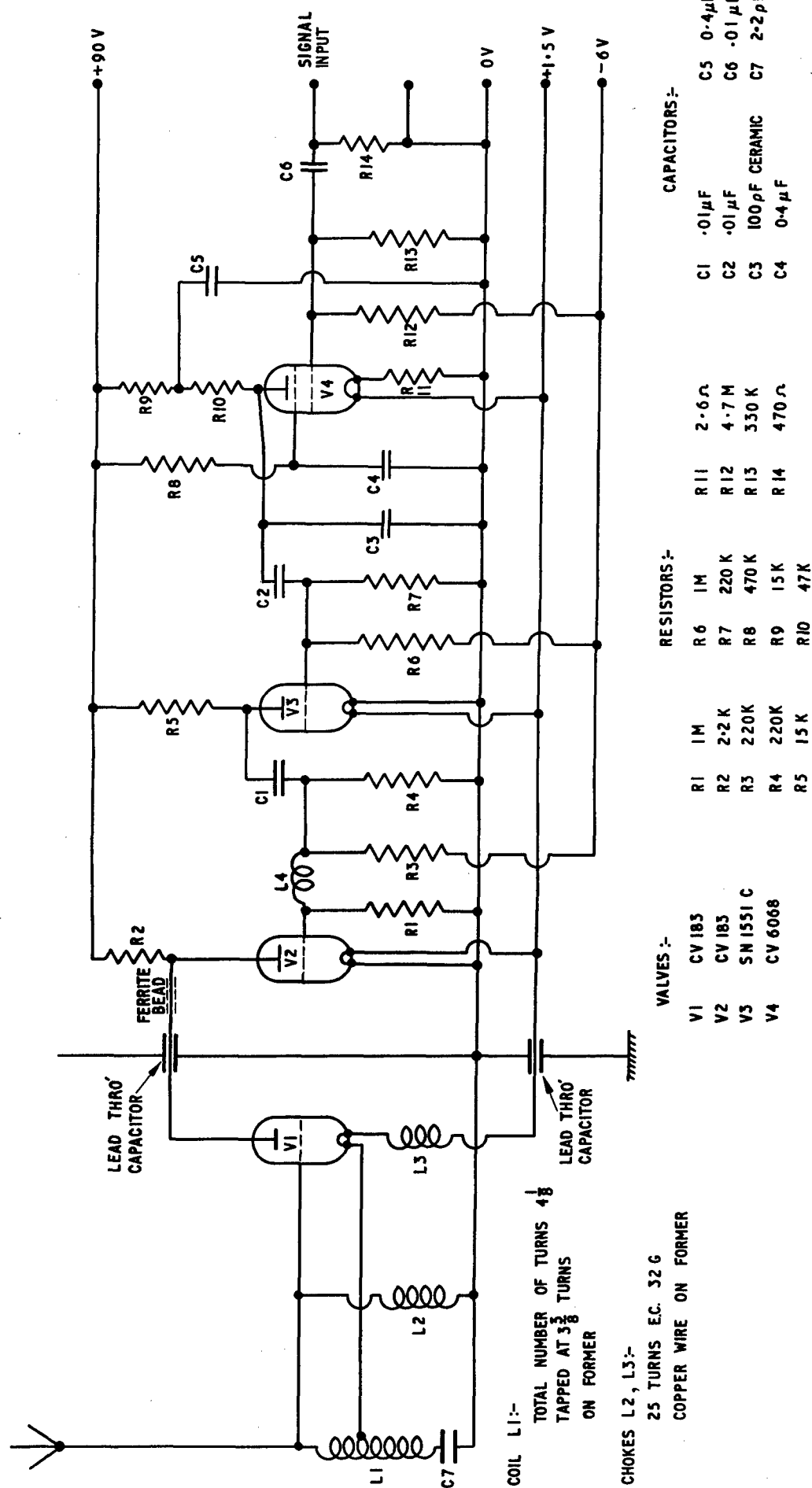


FIG. 4. YAW SONDE AMPLIFIER AND OSCILLATOR

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FIG. 5

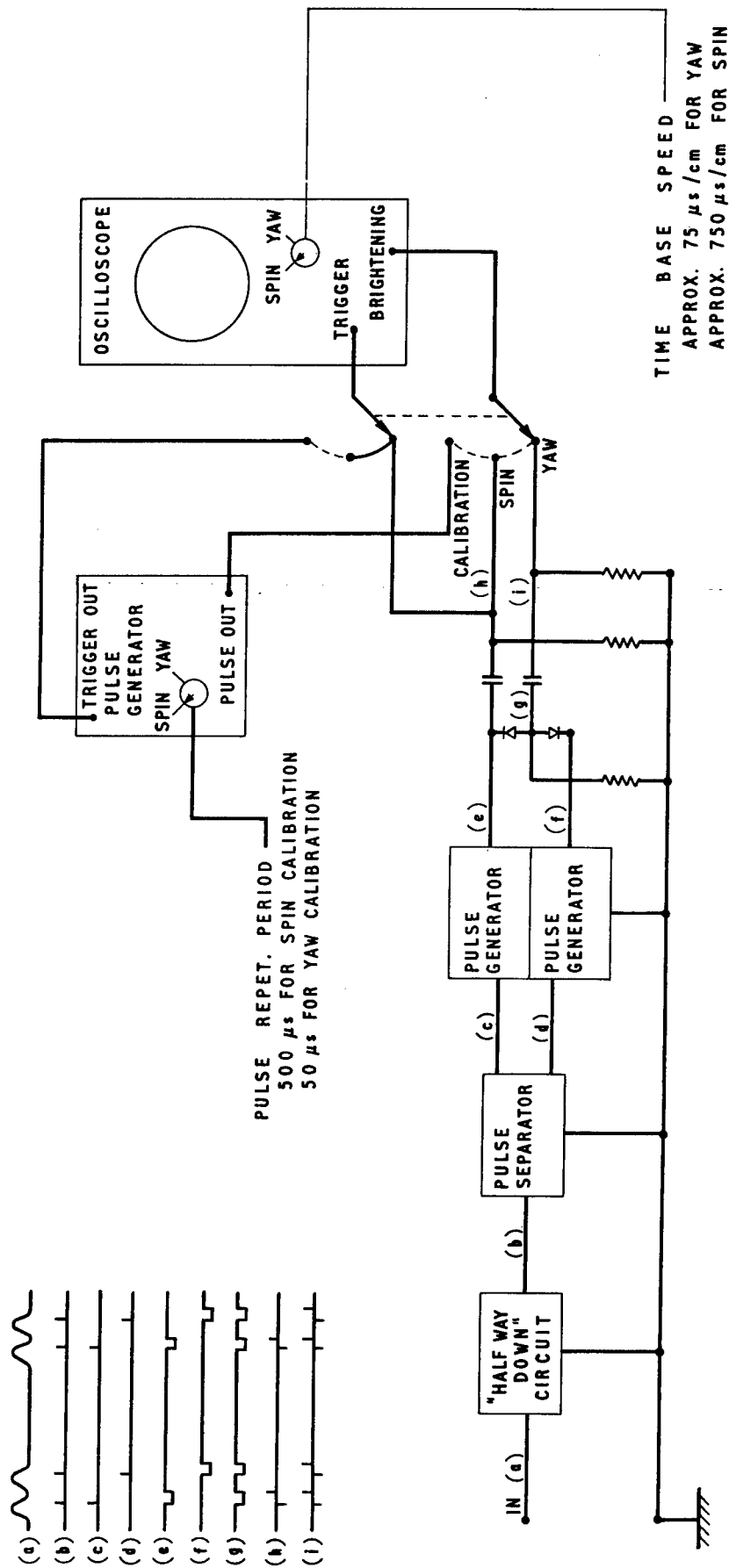


FIG. 5 PULSE UNIT FOR YAW TELEMETRY

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FIG. 6

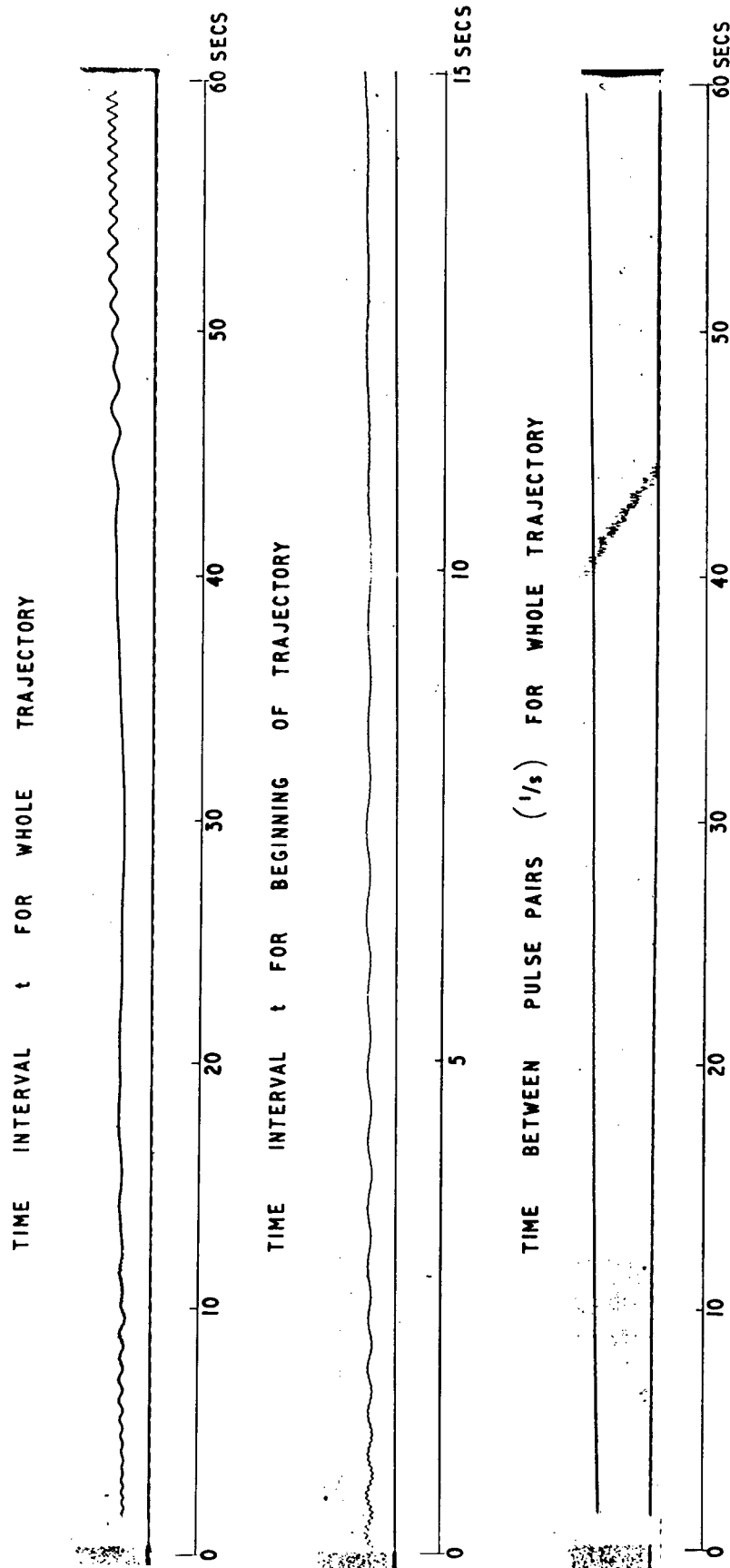


FIG. 6 RECORDED RESULTS

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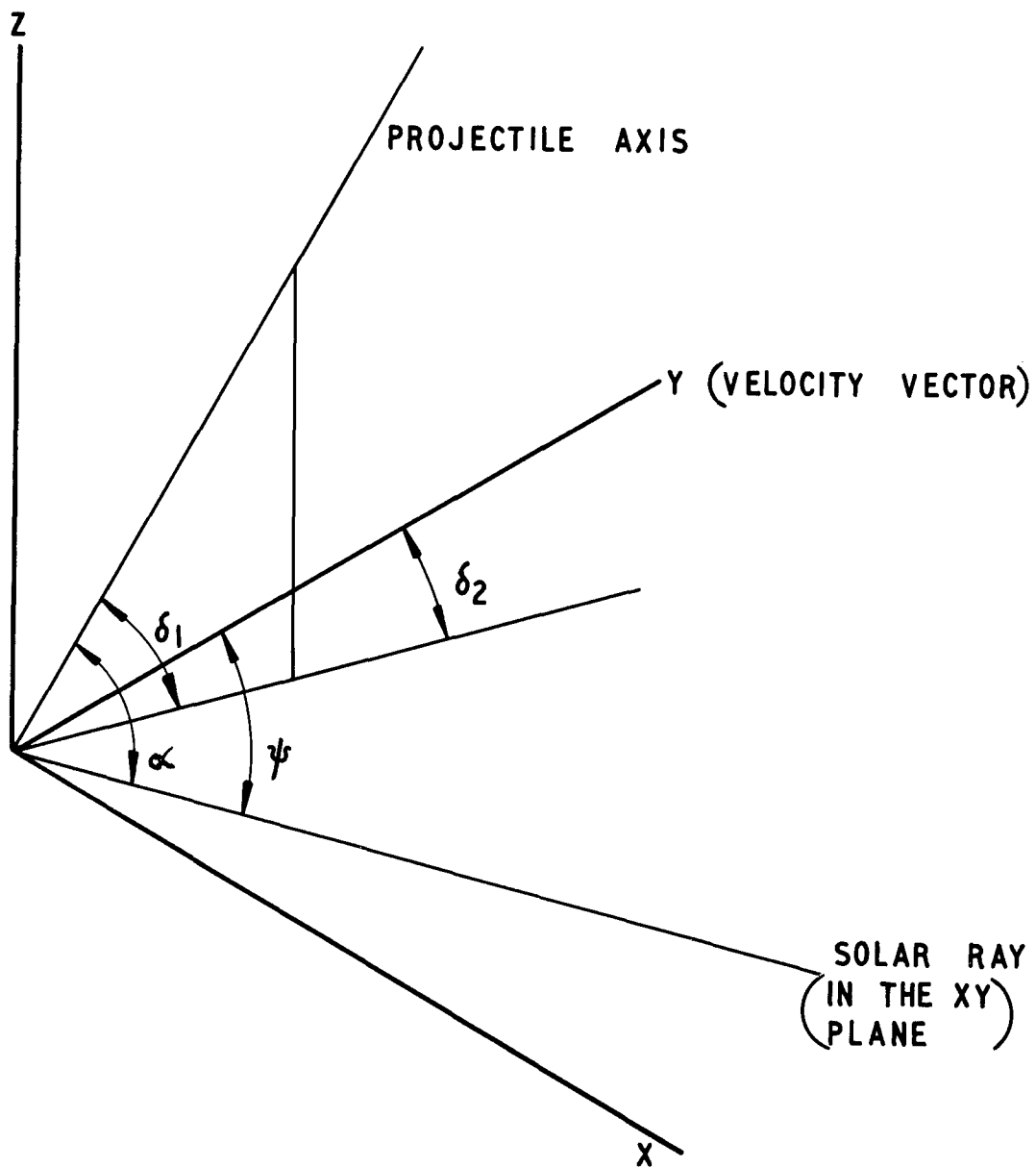


FIG. 7 YAW COMPONENTS IN RELATION TO AXES
OF REFERENCE

Fig. 8

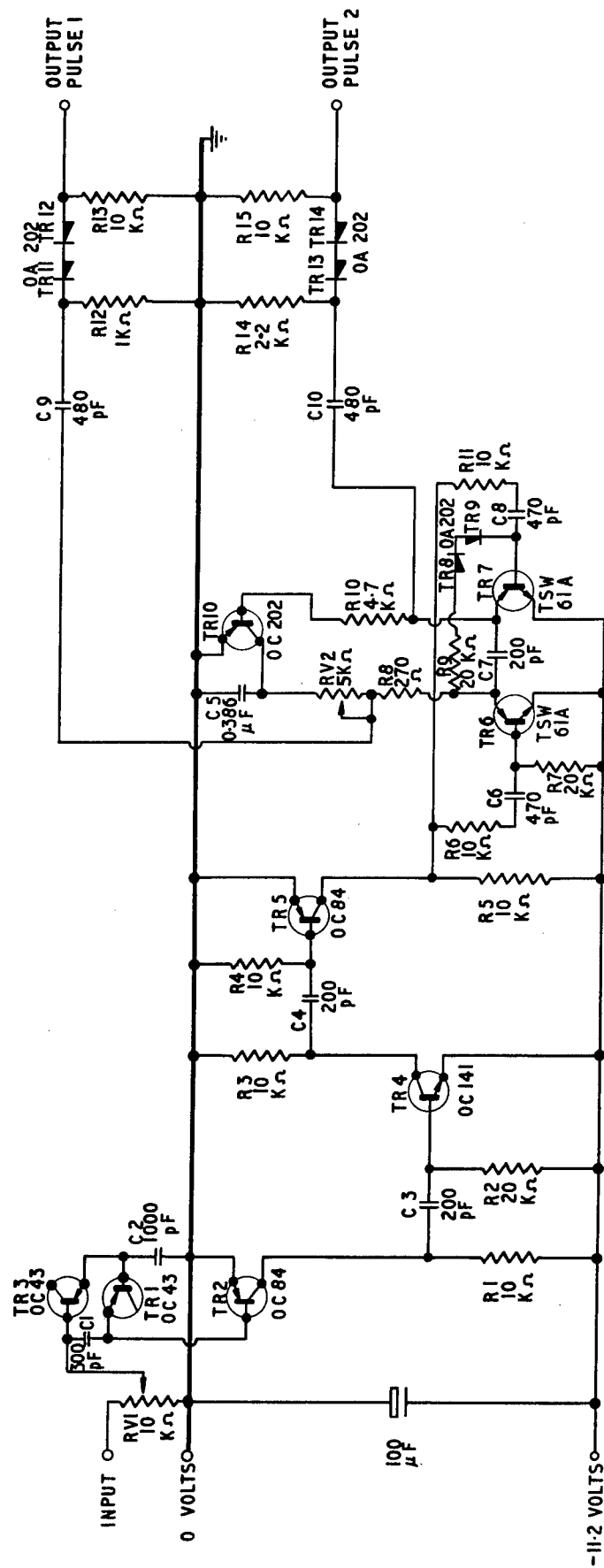


FIG 8 TRIGGER PULSE GENERATOR AND SEPARATOR

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FIG. 9

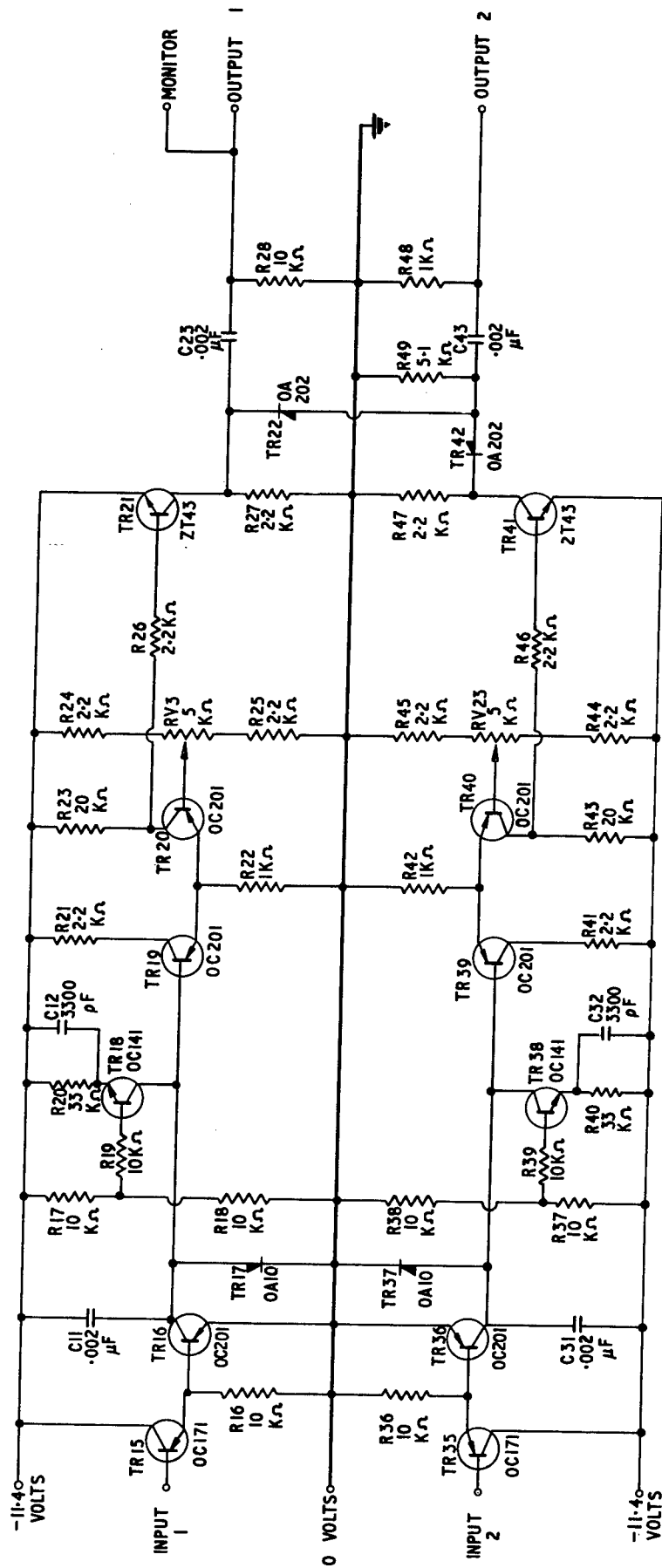


FIG. 9 OUTPUT PULSE GENERATORS

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Royal Armament Research and Development Establishment
R.A.R.D.E. Report 1/65

531.561:
621.398

A telemetry system for the measurement of the yaw of a projectile throughout the major part of its trajectory

I. O. F. Amery, H. G. E. Henning, K. G. A. Lawrie,
E. J. M. Wlatnig.

March 1965

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